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Field performance in agricultural settings of a wireless temperature monitoring system based on a low-cost infrared sensor

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ABSTRACT

Continuous measurement of plant canopy temperature is useful in both research and production agriculture settings. Industrial-quality infrared thermometers which are often used for measurement of canopy temperatures, while reliable, are not always cost effective. For this study a relatively low-cost, consumer-quality infrared thermometer was incorporated into a wireless monitoring system intended for use in plant physiological studies and in agricultural production settings. The field performance of this low-cost wireless system was compared to that of a typical research system based on an industrial-quality infrared thermometer. Performance was evaluated in terms of: reliability of data acquisition, quality of seasonal temperature measurements, seasonal stability of the consumer-quality infrared sensor, and the equivalence of temperatures measured by the consumer-quality and industrial-quality temperature sensors. Results indicate that for many common uses of plant temperature data, the two sensors provide functionally equivalent results. The cost savings and ease of use associated with the low-cost wireless temperature monitoring system present advantages over the higher-cost industrial-quality sensors which may make them a viable alternative in many agricultural settings.

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1. Introduction

Environmental temperature is dynamic on both diurnal and seasonal time scales. Because plants are first and foremost biochemical systems, they are affected by temperature in virtually all aspects of their growth and development. Air temperature and plant temperature are often similar, particularly during darkness, and air temperature is often considered to be a suitable approximation of plant temperature. In arid environments, plant temperatures can range from significantly less than air temperature under optimal water status to significantly higher than air temperature when plant water status is less than optimal. Thermometers, thermocouples, and thermistors provide relatively straightforward measurement of air temperature. Even though plant temperature can be difficult to measure, the value of such measurements is well established (Pinter et al., 2003).

Temperature sensors that require direct contact with the plant (e.g. thermocouples and thermistors) are useful for point-in-time measurements but are ill suited for continuous measurement of plant temperature. Non-contact measurement of plant temperature, which is potentially useful in many situations, can be accomplished through the use of radiometric surface thermometers commonly referred to as infrared thermometers (IRTs). The advantages of infrared thermometry in studies of plant temperature include: no requirement for physical contact with the plant, capability for continuous measurements, and the ability to automate data collection. Additionally since an IRT measures the temperature of the material within its field of view, the temperature measured by the IRT can represent a collection of leaves comprising a canopy.

The cost and complexity of infrared thermometers have changed significantly over the 30 years that they have been used in agricultural settings. For example, the IRTs that were used in our laboratory in the mid 1980s required an external power source and had a cost of approximately $ 3000 (USD). Similar instruments today cost approximately $ 1500 (USD). The development of the infrared thermocouple (IRt/c) resulted in increased simplicity and affordability of instruments for temperature measurements. Industrial-quality IRt/cs (IQIRT) are commercially available from a number of manufacturers and have been used to monitor plant canopy temperatures in studies involving detection of plant water stress (Wanjura and Mahan, 1994; Pinter et al., 2003; Peters and Evett, 2004). Industrial-quality IRT devices are widely considered suitable for use in both research and agricultural production settings.

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Low-cost infrared temperature sensors have become widely available in the past few years. These lower-cost devices are very simple to use and are marketed for use in toys, home electronics, and other non-critical applications. Mahan and Yeater (2008) recently investigated the utility of a low-cost IRT sensor as a replacement for the more expensive IQIRT sensors. They used the term "consumer-quality IRT" (CQIRT) to differentiate these devices from the higher-cost and higher-quality IQIRTs. The results of their study indicated that a CQIRT sensor would be an appropriate substitute for the more expensive IQIRT sensors in certain research and agricultural settings. A wireless IRT system based upon a CQIRT sensor has been developed and is now commercially available (Smartfield.net).

In this study we report the results of field and laboratory analysis of the functionality of the low-cost CQIRT sensor incorporated into a wireless IRT system. The objectives of the study were to: (1) delineate conditions under which the CQIRT system will be equivalent to more costly IQIRT systems; (2) document the ability of the CQIRT devices to detect and quantify canopy temperature differences in the field; (3) assess the stability of the devices on a seasonal timeframe; (4) determine reliability of data transmission on a seasonal timeframe under field conditions. The hypothesis of this study is that a CQIRT sensor, incorporated into a wireless data collection system, will provide seasonal data of sufficient quality to replace IQIRT devices for continuous monitoring of plant canopy temperatures on a seasonal timeframe in the field.

2. Materials and methods

2.1. Wireless infrared thermometry system for CQIRT

The wireless infrared thermometry system used in the study is a Smartcrop© Automated Crop Stress Monitoring System (Smartfield Inc., Lubbock, TX, U.S.A.). The Smartcrop© system uses a Zytemp model TN901 infrared thermometer (Zytemp HsinChu, Taiwan R.O.C.) as a temperature sensor. The use of this consumer-quality IRT (CQIRT) for agricultural applications has been reported by Mahan and Yeater (2008). The Smartcrop© system consists of a base/controller unit and 1–16 remote IRT units. The base/controller serves as a data logger that collects data from remote IRTs at a user-defined interval and provides storage and retrieval of the collected data. Data collection from the base/controller can be accomplished via serial communications' interface that can be directly connected to a computer or various wireless communication devices (e.g. cell phone or UHF radio). The remote IRT consists of a CQIRT sensor (Zytemp) and the electronics necessary for acquiring, storing, processing, and transmitting temperature measurements. The remote IRTs can record the temperature output at a 1-min interval. Temperature values collected by the remote IRTs are averaged every 15 min and transmitted to the base/controller on 15-min intervals via a low-power radio link. Both collection and transmission time-intervals can be defined by the user. The base/controller stores temperature data in on-board memory for subsequent retrieval. The remote IRTs reliably transmit data up to 200 m with a low-cost dipole antenna (170 mm × 10 mm MHW series dipole Antenna Factor, Merlin, OR, U.S.A.) on the base/controller and an omni-directional 1/4 wave antenna on the remote IRT. The Smartcrop© system was installed in an open area with no interfering structures between the base/controller and the remote IRTs. Topography and interfering structures will reduce the transmission range. The remote IRTs are powered by 4 AAA batteries that are user replaceable. Replacement of the batteries every 60 days provided adequate operational power.

2.2. Industrial-quality infrared thermometry system

The "wired" temperature monitoring system used for comparisons to the Smartcrop© wireless system is representative of typical installations in our laboratory over a 10-year period. The infrared sensor used in this system was an Exergen model IRt/c.2 type K 27C (Exergen, Watertown, MA). This sensor, which will be referred to as the industrial-quality IRT (IQIRT), is recommended by the manufacturer for use in agricultural applications. The IQIRT was connected to a Campbell Scientific CR1000 data logger for recording temperatures. The data collection interval was 1 min with 15 min averages calculated and stored for retrieval. Thermocouple extension wire was used to connect the IRTs to the data logger in the field.

2.3. Assessment of data loss rate of CQIRT system

Between December 2007 and March 2008 cotton canopy temperatures were collected in the field in Narrabri, NSW, Australia. Twenty remote CQIRTs and 2 base/controllers (10 remote CQIRTs per base/controller) were installed in an experiment that consisted of 5 irrigation treatments with 4 replicated plots in each treatment. One remote IRT was installed in each replication of each irrigation treatment. The remote IRTs were installed in the field on 24 December at an angle of approximately 70° and a height of 10 cm above the canopy and were adjusted periodically to maintain a distance of approximately 10 cm from the canopy. This distance from target resulted in a field of view that was approximately 10 cm in diameter. The IRTs were installed on the south side of the canopy to prevent shading of the canopy.

2.4. Comparisons of pre- and post-season performance of Smartcrop© remote IRTs

In this analysis the temperature readings of 10 remote CQIRTs (randomly selected from the set of 20) were compared to a thermocouple reading in October of 2007 and again in April of 2008 following more than 80 consecutive days in the field and two trans-Pacific shipping flights (U.S.A. to Australia and return). Pre- and post-season performance of the Smartcrop© remote IRT units was assessed in the laboratory at constant temperatures with a controlled temperature system that uses a set of thermoelectric controllers to maintain specified temperatures in a series of aluminum target blocks (7.5 cm × 5 cm). The surfaces of the thermal blocks were covered with copper plates that were maintained at a specified temperature through the thermoelectric controller. The temperature of the thermal block during each measuring period was monitored with a fine-wire thermocouple (type K) attached to an Omega Model HH21 microprocessor thermometer (Omega Engineering Inc, Stamford, CT). The temperature of the thermal blocks was adjusted through a 10–50 °C thermal range to provide a range of temperatures for assessment. For each temperature reading the Smartcrop© remote IRTs were fixed at 2.5 cm above and perpendicular to the thermal plate. Five measurements were made and recorded at 10-s intervals with the Smartcrop© remote IRT and the thermocouple for each temperature setting.

2.5. Comparison of consumer-quality and industrial-quality IRTs

Canopy temperatures were monitored in a cotton canopy using 16 IRTs (8 Smartcrop© remote CQIRTs and 8 IQIRTs) in Lubbock, TX over a 30-day period between 16 July and 15 August 2008. The plants were grown under 2 irrigation levels (6 mm per day and 2 mm per day via subsurface drip) to provide a broad range of canopy temperatures. The 16 IRTs were installed in the field on 8 July 2008. Four CQIRT sensors (Smartcrop© remote IRTs) and 4 IQIRTs were installed in each irrigation treatment. The 8 CQIRTs

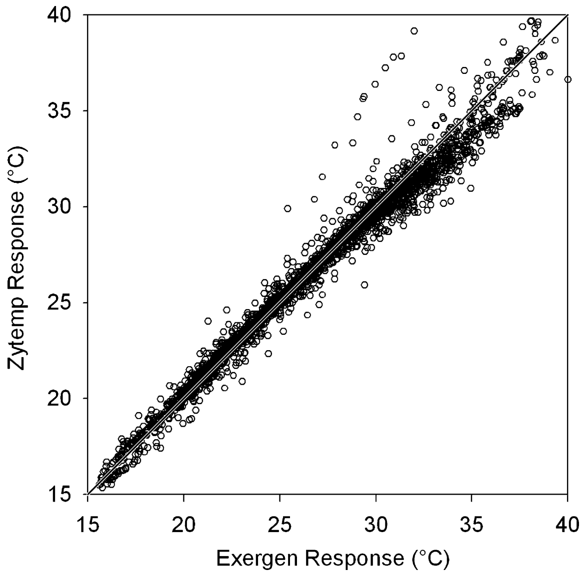

Fig. 1. Comparisons of temperature readings from 8 consumer-quality IRTs (Zytemp) and 8 industrial-quality IRTs (Exergen) over a 30-day period (16 July–15 August) in a cotton field in Lubbock, TX.

were installed at an angle of approximately 70° and a height of 10 cm above the canopy (resulting in a field of view that was approximately 10 cm in diameter) and were adjusted periodically to maintain this distance. The 8 IQIRTs were installed at an angle of approximately 70° and a height of 20 cm above the canopy (resulting in a field of view that was approximately 10 cm in diameter) and were adjusted periodically to maintain this distance. All IRTs were installed on the north side of the canopy to prevent shading of the canopy. Data from the remote CQIRTs was collected as 15-min means of 1 min readings by a Smartcrop© base/controller and data from the IQIRTs was collected as 15-min means of 1 min readings with a Campbell Scientific CR1000 data logger. Principal component analysis (PCA) was used to summarize all variability in temperature readings as well as relationships among the 16 IRTs. PCA was conducted using R software (R Development Core Team, 2008).

3. Results/discussion

3.1. Comparison of IQIRT and Smartcrop© remote IRTs (CQIRT) in the field

The IQIRT used in this study (Exergen model Irt/c.2 K27C) has been used for the continuous determination of canopy temperatures in a large number of agricultural studies over the past decade and is recommended by the manufacturer for such applications. In an earlier paper, Mahan and Yeater (2008) used 5 days of field data to compare the canopy temperatures measured by IQIRTs with those measured by CQIRT (Zytemp) sensors in a prototype wireless remote IRT package. In the current study, we sought to more fully define the differences between the two IRT types, and paired them for measurements of canopy temperature in a cotton field with 2 irrigation treatments in Lubbock, TX over a 30-day measurement interval during the summer of 2008 (16 July–15 August). Fig. 1 regresses the patterns of canopy temperature collected over the 30-day interval. The canopy temperatures are the mean of 15 min of measurements collected at 15-s intervals.

Principal component analysis (PCA) is a multivariate technique that allows relationships among multiple variables to be displayed in as few as two dimensions (i.e., principal component axes, PC1 and PC2). It can be based on either covariances or correlations, and it is a useful approach for investigating the degree to which variables covary over time. We used PCA, based on correlations among the 8 IRTs within each treatment, to summarize all variability in temperature readings. Results of the PCA were illustrated in a biplot (Fig. 2), where each observation ($n = 2076$ per treatment) is plotted using scores for PC1 and PC2. Arrows, representing the contribution of each sensor to each axis, were used to illustrate the relationships among the 8 IRTs. PCA was conducted using R (R Development Core Team, 2008). Together, the first two axes of the PCA accounted for 98.8% (Treatment A) and 99.0% (Treatment B) of the variability within the 30 days of temperature measurements from the 16 IRTs (Fig. 2). Moreover, results of the PCA indicate a high degree of consistency among all IRTs. In both treatments, all IRTs were predominantly related to PC1, which accounted for >98% of the variability. However, there were small systematic differences between IRT types, with the Zytemp and Exergen sensors clustering together on PC2. On a few occasions, the Zytemp sensors overestimated temperatures compared to the Exergen sensors (seen as the points with high values of PC2). Nevertheless, PC2 only accounted for <1% of the total variability, regardless of treatment.

Overall, within an irrigation treatment the canopy temperatures collected by the two types of IRTs are remarkably similar. As previously discussed it is very difficult to separate temperature differences between two locations in the canopy from differences that are a result of the different types of IRT sensor. Thus differences ascribed to differences between IRT types may be exaggerated. The temperatures measured by the two types of IRT sensors agree within ±0.5 °C which is within the ±2 °C range specified accurate by the respective manufacturers. Thus, for the purposes of this study, they appear to be functionally equivalent.

3.2. Quality of the collected data

While a wireless IRT system provides enhanced ease of use, the lack of a physical connection between the IRT and its base/controller presents the possibility of transmission-related data loss. The extent of data loss was assessed in an experiment in which cotton canopy temperatures were monitored in a cotton field in Australia during the 80-day period between 31 December 2007 and 19 March 2008. A perfect transmission rate over the 80-day analysis interval would have produced 7680 temperature measurements for each of 20 IRTs. However, one documented retrieval error

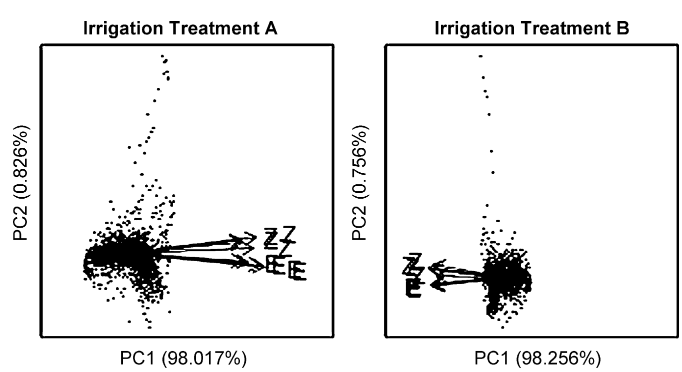

Fig. 2. Biplot of the principal components analysis of the temperature measurements made by the Zytemp (Z) and Exergen (E) sensors in two irrigation treatments. The PCA summarizes variation in 8 dimensions (8 sensors per treatment) using only 2 dimensions (PC1 and PC2). Each axis represents a linear combination of the 8 sensors, and percent of overall variability accounted for by each axis is denoted in the axis labels. Individual points represent the observations (i.e., temperature readings) at each time point, and there were a total of 2076 measurements made over the course of the study. To illustrate the relationships among the sensors, correlations were calculated between temperature readings from each sensor and each PCA axis, and these correlations are reflected in the arrows. All sensors were highly correlated with PC1, and PC1 accounted for the majority of variation in both treatments.

Table 1
Ranking of successful transmissions (% of 7680 total per sensor) and days when 100% of transmissions (96 total per sensor) were successfully received by the receiver base for 20 Smartcrop© CQIRT sensors. Sensors were monitoring a cotton canopy in Narrabri, NSW, Australia over an 80-day period.

Rank	Sensor ID	Successful transmissions (%)	Days with transmission (%)
1	5	99.9	92.6
2	11	99.9	88.9
3	18	99.8	90.1
4	1	99.8	85.2
5	7	99.8	84.0
6	8	99.4	85.2
7	13	99.1	85.2
8	9	99.1	75.3
9	20	99.0	88.9
10	19	99.0	85.2
11	3	99.0	82.7
12	4	98.9	85.2
13	12	98.3	79.0
14	14	98.1	82.7
15	6	97.8	66.7
16	17	97.1	80.2
17	10	95.0	69.1
18	2	93.7	66.7
19	16	93.1	48.1
20	15	88.3	54.3
Average		97.7	78.8
Two best IRTs combined (5 and 11)		100.0	98.8
Two worst IRTs combined (15 and 16)		99.5	72.8

during the experimental interval resulted in the loss 19 measurement points for all 20 remote IRTs resulting in 7661 possible data points per IRT. Table 1 shows the performance of the 20 remote IRTs over the measurement interval. The percentage of successful transmissions for the remote IRTs varied from a low of 88.3% to a high of 99.9%. The average for all 20 remote IRTs over the experimental interval was 97.7%. In our experience IRTs are commonly installed in pairs within experimental units. When the two worst performing remote IRTs were paired for analysis, at least one valid measurement was available 99.5% of the time. This result suggests that a pair of remote IRTs should provide effectively continuous monitoring of canopy temperatures.

Reliable transmission of temperature measurements from the IRT is an important consideration in the use of a wireless data collection system. The wired IQIRT systems are generally quite reliable with data errors generally limited to problems with degradation of thermocouple wiring that connects the IRTs and the data logger. Wiring problems are typically a result of mechanical problems with wiring resulting from equipment and personnel moving within the experiment or rodent damage. These errors are generally readily detectable and easily repaired by replacement of the damaged wire. In the case of the wireless IRT system there is no wire that can be damaged. However, the radio transmissions between the remote IRT and the base/controller are subject to error. Factors that have the potential to affect the successful transfer of data between the remote IRT and base/controller include; transmission range, battery status of the remote IRTs, and the number of remote IRTs associated with a given base/controller.

The successful transmission range for data varies according to the type of antenna that is attached to the receiver. While the antenna attached to the receiver can be changed, the antenna in the remote IRT is fixed. In this experiment the antenna attached to the base/controller was an inexpensive dipole antenna. There was no correlation between the distance from a remote IRT to the base/controller at distances between 100 m and 200 m (data not shown) suggesting that the dipole antenna has a reliable range of at least 200 m. Informal analysis using other antenna designs (YAGI and omni-directional) indicates that reliable communication can be achieved at a distance of 1000 m.

The remote IRT is powered by 4 AAA batteries inside the unit that provide sufficient power for reliable transmissions for approximately 60 days at a data transmission interval of 15 min. Battery voltage is included for each data point and can be monitored thus allowing replacement of batteries prior degradation of data transmission. The remote IRTs conserve battery power by activating their radio transmitters (for less than 5 s) on 15-min intervals in order to transmit 15-min averages to the base/controller. The radio receiver on the base/controller is continuously in a “receive” mode. As the number of remote IRTs associated with a base/controller increases, the probability of a failure to receive a 15-min transmission increases. Testing indicates that a base/controller can effectively communicate with up to 16 remote IRTs.

3.3. Quantitative analysis of canopy temperatures

In the experiment conducted in NSW, Australia cotton, the remote IRTs effectively measured diurnal and seasonal variation in canopy temperature and detected the differences in canopy temperature that are associated with irrigation treatments (Table 2). Though the range of canopy temperatures varied among the treatments (see Table 2), the standard errors of the 30-day means of the 4 remote IRTs in each irrigation treatment were quite similar.

Temperature data from 3 representatives of the 5 irrigation treatments is presented in Fig. 3. The diurnal patterns of mean canopy temperatures over a representative 30-day interval from 6 February to 7 March 2008 of the Australian field study is shown for the means of the 25%, 50% and 100% irrigation treatments in Fig. 3. The mean of each treatment represents 4 remote IRTs in each of the irrigation treatments. Differences among the treatments are evident. The standard error of the mean among the remote IRTs in each treatment represents both the variability among the 4 remote IRTs in the treatment and the variability in canopy temperature among plants in the treatments (Fig. 3). Since it is infeasible to simultaneously monitor the temperature of identical portions of the canopy with multiple remote IRTs, the two sources of error cannot be effectively separated. Given the combined sources of error the observed pattern of standard error suggests that the remote IRTs are capable of providing continuous canopy temperature data of the quality needed for metabolic and water deficit studies.

Table 2
Summary of canopy temperature measured over an 80-day period (31 December 2007–19 March 2008) in a cotton field in Narrabri, Australia. Irrigation treatment indicates targeted percentage of daily ET replaced on a two-day irrigation interval.

Irrigation treatment	Mean temperature	Minimum temperature	Maximum temperature	Standard error
25	23.1	10.2	39.9	0.066
50	22.6	10.1	37.5	0.059
75	22.1	10.2	34.5	0.054
100	21.9	10.1	33.3	0.052
125	21.8	10	31.2	0.049

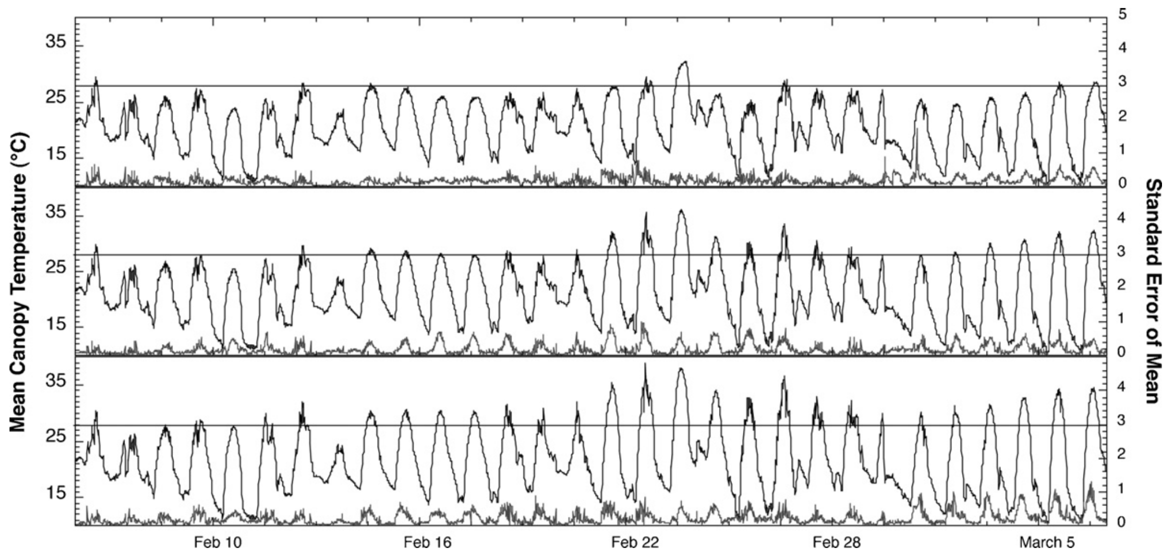

Fig. 3. Mean canopy temperatures and standard error over a 30-day interval (6 February–7 March) for a cotton field in Narrabri, NSW, Australia. Three irrigation levels; 25%, 50% and 100% represent differential irrigation treatments designed to replace the designated fraction of ET on a 2-day irrigation interval. The means are of 4 remote IRT devices in each of the water treatments with the standard error of the mean shown for each treatment. The horizontal line in the figure marks the 28 °C value for cotton optimal temperature.

3.4. Pre- and post-season temperature stability

In order to determine the stability of the Smartcrop© remote IRTs over time, temperature readings of 10 of the remote IRTs were compared to temperature readings of thermocouples using a controlled temperature device before and after a field deployment. A comparison of the results of the pre- and post-season temperature tests is shown in Fig. 4. A linear regression analysis of the remote IRT readings as a function of the temperature of the target, as determined by a thermocouple, results in similar behavior. The zero intercepts (0.94 for pre-season versus 1.46 for post-season) and slopes (1.04 for pre-season versus 0.96 for post-season) differed slightly while the correlation coefficients were identical ($r = 0.998$). There does not appear to be a functionally important change in performance over the growing season. It is perhaps worth noting that the Zytemp sensor units can be replaced in the remote IRTs for approximately $ 20 (US) so there would be no pressing need to use sensors over multiple seasons.

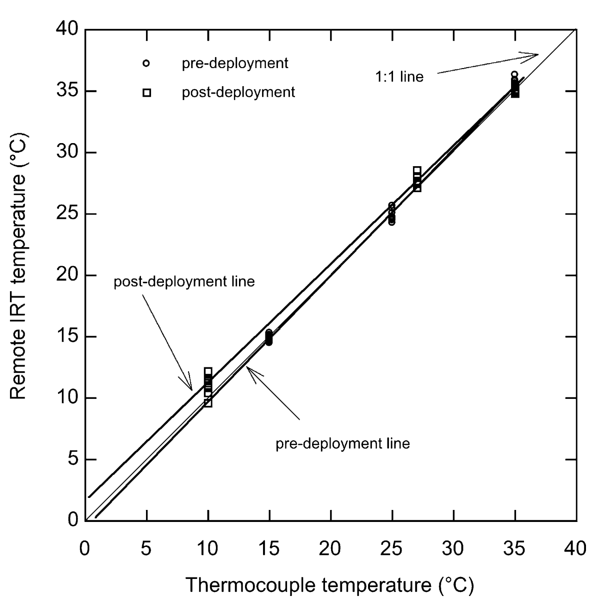

Fig. 4. Comparison of temperature readings from 10 consumer-quality IRTs before and after deployment in a cotton field in Narrabri NSW Australia during the summer of 2008. Temperature of a constant-temperature target was measured in the laboratory with both the consumer-quality IRT and a thermocouple. Each point represents the mean of 5 measurements made sequentially at 10-s intervals. Standard errors of the means are smaller than the data markers. Regression lines are shown for pre and post deployment values along with a 1:1 line.

3.5. Utility of the Smartcrop© system in research and production settings

One goal of this study was to determine the suitability of the Smartcrop© IRT system as a replacement for the higher-cost IRT devices that are commonly employed for irrigation control and physiological studies in plants. The lower cost of the CQIRT system, in comparison to the IQIRT, will allow for the deployment of an increased number of IRTs for a given cost and thus provide more measurements of plant canopy variability. Four common uses of plant canopy temperature are discussed in the following paragraphs.

The use of continuous measurement of canopy temperature has been used in irrigation scheduling by the BIOTIC method (Wanjura and Mahan, 1994; Wanjura et al., 1995; Mahan et al., 2005). This method compares measured canopy temperature to a biologically identified estimate of optimum plant temperature to provide an indication of the water status of the crop. The biological thermal optimum, which is used to interpret canopy temperatures, is a laboratory-derived value that typically is determined at a resolution of ±0.5 °C. It is evident that the results of temperature measurement with the Smartcrop© IRT devices, which is within the ±0.5 °C range, would be suitable for use in implementing the BIOTIC irrigation scheduling method.

Plant canopy temperatures have been used to document differences between canopy and air temperatures. The relationship between canopy temperature and air temperature has been used as a tool for identifying plants with enhanced performance under water deficit conditions (Balota et al., 2007). Canopy temperature depression (CTD), the differential between ambient air and plant canopy temperatures, is a tool that has been used to interpret and evaluate plant response to environmental stress. Balota et al. (2007) reported canopy temperature depressions in winter wheat that ranged from 10 to 3 °C. Similarly, in another study conducted on spring wheat (Amani et al., 1996) there were differences in mean canopy temperature depressions ranging from −2.8 °C (early season) to −8.2 °C (late season). Canopy temperature differences of this magnitude could be detected and quantified using a Smartcrop© IRT system.

The relationship between plant temperature and metabolic responses has been used to define metabolic limitations on plant metabolism in agricultural systems. Examples of the use of canopy temperature measurements in metabolic studies include: modeling of seedling emergence (Mahan and Gitz, 2007); prediction of in vivo enzyme function (Mahan, 2000); and prediction of herbicide efficacy and resistance (Light et al., 2001; Mahan et al., 2006). In each of these approaches, the resolution of temperature that can be achieved in the laboratory is on the order of ±1 °C. The results of this study indicate that the Smartcrop© remote IRT is capable of providing plant temperature data at an appropriate resolution for such analyses.

The suitability of the Smartcrop© IRT system is ultimately dependent on the intended use of the temperature data collected by the device. In regard to the above-mentioned uses of plant canopy temperature in plant research and production, it is concluded that the Smartcrop© IRT is sufficiently accurate for each use. There are uses of plant canopy temperature that require resolution of temperature on a finer scale than is possible with the Smartcrop© devices (Kacira et al., 2002; Xiao et al., 2006) for such uses, IQIRTs would be more appropriate instruments.

4. Conclusion

The primary advantages of the Smartcrop© IRT system compared to the more widely used IRTs include: (1) wireless operation that is more suitable in many research and production applications and (2) reduced cost that, for a given expenditure, could allow for the deployment of a larger number of devices for a given expenditure. The results of this initial study indicate that the CQIRT sensors incorporated into the Smartcrop© remote IRT system provide resolution and reliability that are sufficient for many common uses of continuously monitored plant canopy temperatures.

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